Threshold effects of energy price changes

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SOM-theme C Coordination and growth in economies

Abstract

This paper presents a theoretical model emphasising energy investments' characteristics of uncertainty and irreversibility. The theoretical model suggests threshold effects. Firms are induced to substitute away from energy only if prices of energy exceed a certain threshold level and they reverse the technology only if energy prices are low enough. Estimating a simple investment relation using panel data for the Dutch economy, we find evidence for threshold effects.

Keywords: threshold effects, energy substitution, environmental policy
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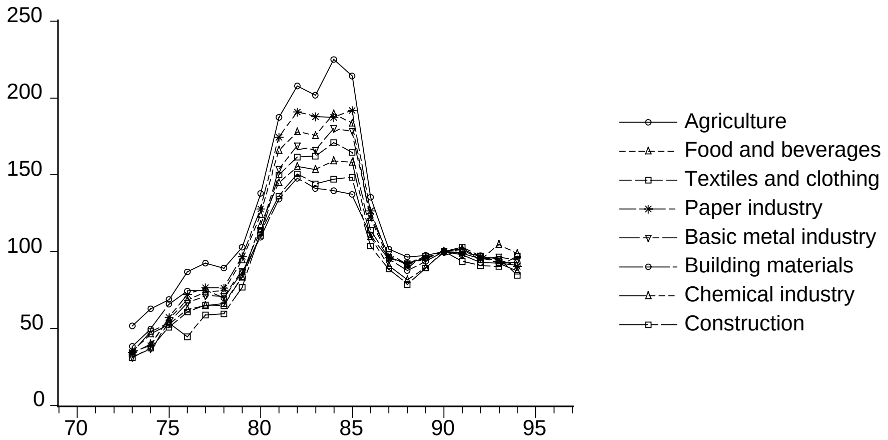
1. Introduction

Governments of most developed countries aim to substantially reduce energy use to limit the emission of greenhouse gases (such as carbon dioxide). The effectiveness of taxing energy use depends on the substitution elasticity between inputs in production and on technological progress. Analysis of past experience may give insight in the potential effectiveness of energy taxation to induce a decrease in energy use.

Examination of the data indicates that the 1973-1994 period can be divided in two sub-periods. From 1973 to 1986, energy prices went up, while prices have been observed to fall quite substantially in later years, as can be seen from Figure 1.[1]

Figure 1 *Energy prices (1990=100) for eight sectors of industry of the Dutch economy for the period 1973-1994.*



This subdivision may be important as the economic consequences of energy price increases and decreases are generally not symmetric. The literature on the potential causes of asymmetric responses to energy price increases and decreases has focused

[1] Sectoral energy prices have been calculated on the basis of the share of the various energy carriers in a sector's energy use.

on the importance of irreversibility. If adjustment to changes in relative prices involves adaptation costs, economic agents have an incentive to postpone the adjustment. The incentive to postpone is even stronger when there is uncertainty about the persistence of the change. If adjustments are costly and the future is uncertain, the option value of waiting increases because new information is likely to arrive over time, which may exceed the foregone benefits of adjusting straightaway. This idea has been applied at various levels in the economy. The literature focusing at the sectoral level, initiated by Hamilton (1988), attacks the idea that production factors are able to relocate smoothly from one sector to another. If production factors (mainly capital and labour) are specialised, it may be optimal not to immediately leave adversely affected sectors and to move to positively affected sectors, but to remain unemployed and wait for conditions to improve. At the micro level, firms are likely to postpone irreversible investment expenditures on both energy-saving technologies and their reversal towards energy-intensive technologies (see for example Bernanke, 1983). This means that firms will not respond immediately to energy price increases; but if they have responded, energy prices will have to fall substantially before the investment is reversed.

Empirical studies seem to corroborate this explanation of asymmetric responses. At the micro-economic level there is evidence pointing to the fact that firms and consumers adapt faster (and stronger) to energy price increases than to price decreases (*e.g.* Bacon, 1991; Borenstein *et al.*, 1997; Gately, 1992; Kirchgässner and Kübler, 1992; Mork, 1989; Ryan *et al.*, 1996). At the macro-level, asymmetries may also be important. It has been observed that economic activity is more strongly affected by increases in the energy price than by decreases (Dargay and Gately, 1994; Gardner and Joutz, 1996; Mork *et al.*, 1994; Mory, 1993; Smyth, 1993). However, not all price increases will have an equally strong impact on investments in energy-saving technologies. If energy prices increase after a period of low prices, the change is merely a recovery that is unlikely to induce additional investments in energy efficiency. Only “all time highs” will induce new investments in energy efficiency (Hamilton, 1996). If such an asymmetric response exists, it has important policy implications. Currently, energy prices are relatively low after a period of significant price increases (1973-1986). This means that (part of the) industry has already geared its technology to higher energy prices in the past.[2] Increasing energy tax rates (as part of environmental policy) in a situation where energy prices are low after a period of high energy prices is therefore expected not to have a strong impact on investment behavior and technology choice, and thus results in only modest reductions in energy use. More likely, firms are forced to simply incur the rise in costs. This means that in order to achieve a substantial reduction in energy use, energy prices should be increased considerably with potentially high costs in terms of, for example, international competitiveness. However, in the post-1986 period, energy prices are much lower and also less subject to fluctuations. Given the positive correlation between the *level* of energy prices and their *variance* (*e.g.* Ferderer, 1996), uncertainty is likely to be smaller in the post-1986 period. As this may also affect the responsiveness of Dutch industry to changes in energy prices (and hence to taxation), the impact of uncertainty should be analyzed. To explore the consequences of irreversibility and uncertainty for the environmental effectiveness of energy taxation in the Netherlands, the mechanisms behind asymmetric responses are elucidated through the use of a simple investment model presented in the next section.

On the basis of this model we show that, following a period of energy price increases, prices will have to drop substantially before energy-saving technologies are to be replaced by energy-intensive ones. This drop is likely to be larger (i) the higher the adjustment costs, (ii) the faster energy prices are expected to increase over time and (iii) the higher uncertainty about future prices. On the other hand if prices do not

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[2] On average, the (economic) lifetime of a installed capital is about 15 to 20 years.

drop enough, *i.e.* not enough to replace energy-saving technologies with more energy intensive ones, energy price increases will not have much impact on energy use, suggesting that energy policy in periods of low energy prices will not be very effective.

The next section presents a theoretical model which shows that there are threshold effects to explain these asymmetries. Section 3 discusses the implications of the theoretical model. In section 4, an empirical analysis is undertaken for eight sectors of Dutch industry to estimate these threshold effects. Section 5 concludes.

2. Investing under uncertainty

In this section, an illustration is provided why asymmetric reponses to energy price changes referred to in the previous section may arise. The main features causing the asymmetric response are the sunk-cost nature of investments in new technologies, exacerbated by the existence of uncertainty about the future. Suppose that there are two alternative technologies available for firms. A given quantity of goods can be produced by either an energy-intensive or a labour-intensive technology. Suppose that inputs for the energy-intensive technology are E_1 units of energy, and L_1 units of labour, while the corresponding inputs for the labour-intensive technology are E_2 and L_2, respectively. From the assumption it is clear that $E_1>E_2$ and $L_1<L_2$. For notational convenience, define $\Delta E=E_1-E_2$ and $\Delta L=L_2-L_1$. Furthermore, assume that the adjustment costs (C_A) from switching either from the energy-intensive to labour-intensive technology or vice versa, are the same.[3]

[3] Note that this assumption seems unnecessarily restrictive. However, dropping it would have clear-cut consequences for the results derived in this section. If adjustment costs from energy-intensive to energy-saving technologies are higher than the reversal (which seems plausible because of, for instance, uncertainty with respect to the performance of new technologies and maybe also because of environmental regulations requiring emission cleaning activities), the conclusions of this section will only be strengthened.

In order to keep things simple we assume that the price of labour (*W*) is constant and known, but that future energy prices (P_E) are uncertain. Since most types of energy currently employed come from depletable resources, we assume a time trend for prices, but disturbances may force the energy price to deviate from its trend path. More specifically, the energy price is assumed to follow a Brownian motion:

(1) $$dP_E = \alpha P_E dt + \sigma P_E dz .$$

In this equation, α is the trend parameter and $dz = \varepsilon\sqrt{dt}$, where ε is a normally distributed independent variable with a zero mean and a standard deviation of 1. This implies that $\mathrm{E}(dP_E)=\alpha P_E\, dt$ with variance $\sigma^2 P_E^2 dt$ (Dixit and Pindyck, 1994, p. 70-71). Therefore, the expected energy price at time *t* equals:

(2) $$\mathrm{E}(P_E(t)) = P_{E_0} e^{\alpha t},$$

where E_o refers to the starting period.

Now the costs and benefits of switching from the energy-intensive technology to the labour-intensive technology can be determined. The change in technology results in savings on energy expenses, but expenditures on labour increase. Taking into account the adjustment costs C_A, the value of switching to labour-intensive (and hence energy-saving) technology equals:

(3) $$\Omega^{ES}(P_E) = \int_0^\infty \mathrm{E}(P_E)\Delta E e^{-rt} dt - \frac{W\Delta L}{r} - C_A = \frac{P_E \Delta E}{r-\alpha} - \left(\frac{W\Delta L}{r} + C_A\right),$$

where *r* is the (exogenously determined) discount rate which exceeds the drift term *α*.[4]

[4] The results have been derived using dynamic programming, which is based on the assumption that the price risk cannot be spanned by constructing an appropriate market portfolio. If we would have dropped this (implicit) assumption, contingent claims analysis could be used which would have enabled us to derive a risk-adjusted discount rate. Using the capital asset market pricing approach, this discount rate would be equal to $r + \phi\rho_{PM}\sigma$,

After implementing the labour-intensive technology, the firm may decide to reverse its investment if the price of energy is sufficiently low (see below). For a certain energy price level P_E, the value of this reversal option equals:

$$(4)\quad \Omega^{EI}(P_E) = \frac{W\Delta L}{r} - \int_0^{\infty} \mathrm{E}(P_E)\Delta E e^{-rt}dt - C_A = \frac{W\Delta L}{r} - \left(\frac{P_E \Delta E}{r-\alpha} + C_A\right).$$

Which energy price level is sufficiently high to induce the firm to switch towards the energy-saving (*i.e.* labour-intensive) technology? In each period, the firm compares the benefits of undertaking the investment (in terms of cost reductions achieved) with the benefits of postponing the decision one period. The benefits of postponing the decision include access to more information about energy prices. Given the uncertainty that the firm faces, postponing the decision reduces the probability of investing when such an investment turns out to be unprofitable. In mathematical terms, the firm maximizes:

$$(5)\qquad F^{ES}(P_E) = \max\left\{\Omega^{ES}(P_E), \frac{1}{1+rdt}\mathrm{E}\left(F^{ES}(P_E) + dF^{ES}(P_E)\right)\right\}.$$

The value $\Omega^{ES}(P_E)$ is labeled the “termination value”. When the firm decides to undertake the investment, its expected return is known. The expected return of waiting (the second term in the brackets) is usually referred to as the “continuation value”. The firm's optimal decision maximizes the net present value of the investment option F^{ES}. As soon as the termination value exceeds the continuation value, the investment is undertaken. The energy price for which this is just the case will be referred to as the critical energy price $P_E^{ES^*}$.

Applying Ito calculus, the following differential equation is obtained:

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where ϕ is the market price of risk and ρ_{PM} the correlation coefficient between market risk and the riskiness of the energy price (see Dixit and Pindyck, 1994, p. 185).

(6) $$rF^{ES}dt = \mathrm{E}\left[F_P^{ES}dP_E + \frac{1}{2}F_{PP}^{ES}(dP_E)^2\right] = \left[F_P^{ES}\alpha P_E + \frac{1}{2}F_{PP}^{ES}\sigma^2 P_E^2\right]dt.$$

If we try the function $F^{ES} = AP_E^{\beta}$ and solve the differential equation, two roots can be found:

(7) $$\beta = \left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right) \pm \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}\ .$$

The term β captures the impact of price uncertainty on the critical energy price level at which the switch towards the energy-saving technology will be carried out. The general solution is of the form $F^{ES}(P_E) = A_1P_E^{\beta_1} + A_2P_E^{\beta_2}$ where β_1 and β_2 represent the roots. One root is positive, $\beta_1>1$, and one is negative, say β_2. The higher the energy price, the higher the value of the energy-saving investment option. This implies that the term with the negative root can be ignored: A_2 equals zero. Then the critical value of the energy price can be determined by using two additional conditions (Dixit and Pindyck, 1994; Pindyck, 1991). First, in the optimum it must hold that at the critical energy price level, the value of the investment project is equal to the termination value: $F^{ES} = \Omega^{ES}$: given the fact the investment is undertaken, waiting apparently no longer has a positive net value (see equation (5)). Secondly, optimality requires that the option value function F^{ES} and the termination value function Ω^{ES} meet tangently at the critical price level: $F_P^{ES} = \Omega_P^{ES}$, where subindex P denotes the partial derivative towards P_E. Using these two additional conditions, it can be found that the critical price level above which a firm invests in an energy-saving technology equals

(8) $$P_E^{ES^*} = \left(\frac{\beta_1}{\beta_1 - 1}\right)\left(\frac{r-\alpha}{\Delta E}\right)\left[\frac{W\Delta L}{r} + C_A\right].$$

This critical price level is positive since $r>\alpha$. Note that according to the NPV rule, the investments would be carried out as soon as:

(9) $$\frac{P_E \Delta E}{r-\alpha} > \frac{W\Delta L}{r} + C_A \,.$$

The critical value under uncertainty, irreversibility and flexibility with respect to the timing of the investment decision exceeds the NPV's critical value because $\frac{\beta_1}{\beta_1 - 1} > 1$ since $\beta_1 > 1$.

After the switch towards the energy-saving technology, the energy price may fall such that the firm may decide to reverse its decision and to re-install an energy-intensive (but labour-saving) technology. In each period, it weighs the benefits of reversing now and the benefits of postponing the switch:

(10) $$F^{EI}(P_E) = \max\left\{\Omega^{EI}(P_E), \frac{1}{1+rdt}\mathrm{E}\left(F^{EI} + dF^{EI}\right)\right\}.$$

Hence,

(11) $$rF^{EI}dt = \left[F_P^{EI}\alpha P_E + \frac{1}{2}F_{PP}^{EI}\sigma^2 P_E^2\right]dt \,.$$

Again, we try function $F^{EI} = AP_E^{\beta}$. Then,

(12) $$\beta = \left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right) \pm \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} \,.$$

This time only the negative root (β_2) plays a role: the lower the energy price, the higher the likelihood that the reversal will be profitable and hence the higher the value of the reversal option. Using $F^{EI} = \Omega^{EI}$ and $F_P^{EI} = \Omega_P^{EI}$, it can be found that

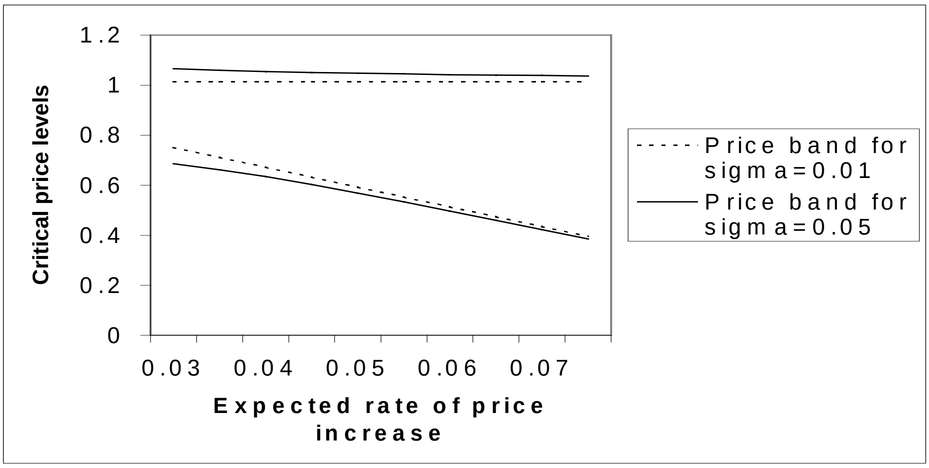
(13) $$P_E^{EI^*} = \left(\frac{\beta_2}{\beta_2 - 1}\right)\left(\frac{r-\alpha}{\Delta E}\right)\left[\frac{W\Delta L}{r} - C_A\right].$$

Again, this critical price level is positive. Note that, because $\beta_2 < 0$, $0 < \frac{\beta_2}{\beta_2 - 1} < 1$ and hence the calculated critical value is lower than the value indicated by the NPV approach.

3. The implications of investing under uncertainty

The analysis presented above implies that there is an asymmetry in the response to energy price increases and decreases. The existence of adjustment costs, high expected rates of energy price increases and uncertainty about future prices drive a wedge between the critical energy price for a switch towards labour-intensive technologies, and the critical price for its reversal. Hence, in response to a price increase, investments will be undertaken. But a subsequent (moderate) drop in energy prices will not induce the reversal towards the energy-intensive technology.

Figure 2 *Inertia price gaps as a function of the expected rate of energy price increases (α), for different levels of uncertainty (σ = 0.01 and σ = 0.05).*
Parameter values: $\Delta E = 1, \Delta L = 1, r = 0.125, W = 1, C_A = 0.1.$



This point is illustrated in Figure 2, where critical energy price lines are drawn for various time trends and for two levels of uncertainty ($\sigma = 0.01$ and $\sigma = 0.05$). From Figure 2 it is clear that there is a gap (an area between the two critical energy price levels) where prices can fluctuate without firms adapting their production technologies. Expectations about future price developments play an important role in deciding whether or not to invest in energy-saving technology. Indeed, the critical price lines demonstrate that a higher (expected) price trend induces the firm to invest sooner (although the reduction is not substantial), but more importantly that the energy price should be much lower before the firm will start contemplating to reverse its decision. The reason is that high trend values compensate for stochastic drops in the energy price. The reversal will thus only take place if the actual energy price is quite low: only then can it be expected to stay at a low level for a substantial period of time (see equation 1). Furthermore, the higher the uncertainty with respect to future prices, the longer a firm will postpone investing: the higher the uncertainty, the larger the inertia gap.

It is clear that the asymmetry in the response to energy price changes will increase with α and σ. If the upper critical level (*i.e.*, switch towards labour-intensive technology) has just been attained, the firm will undertake the investment. However, to reverse that decision, the energy price should drop substantially. For a large range of price decreases, nothing will happen in terms of energy use. The size of the inertia gap is larger (i) the higher the expected rate of price increase and (ii) the more uncertainty about future price levels. Of course, adaptation costs (C_A) also play a role: the higher these costs, the larger the inertia gap.

4. Threshold estimation

We have gathered data on a panel of eight sectors of industry for the Dutch economy: agriculture, food and beverages, textiles and clothing, paper industry, basic metal industry, building materials, chemical industry and construction. These sectors are chosen on the basis of data availability for a longer time period. Data on energy use and energy prices are not (yet) available for the period before 1973 and after 1994 consistent with the 1973-1994 period. Furthermore, not all variables are available for the chemical industry for the period 1973-1976, so we restricted the time period to the period 1977-1994.[5]

The implication of the analysis above is that regression functions are not identical across all observations in the sample: the response to energy price changes is typically asymmetrical. To avoid an arbitrary selection of thresholds we estimate the threshold using threshold regression methods with sector-specific fixed effects (Hansen, 1999). If we have a balanced panel of observations ($i=1,\ldots,n$ sectors and $t=1,\ldots,T$ time periods), we can write the equation of interest as for two thresholds as:[6]

$$y_{it} = \mu_i + \beta_1' x_{it} I(q_{it} \leq \gamma_1) + \beta_2' x_{it} I(\gamma_1 < q_{it} \leq \gamma_2) + \beta_3' x_{it} I(q_{it} > \gamma_2) + e_{it} \tag{14}$$

where x_{it} is a k-vector, and q_{it} is the threshold variable and γ_1 and γ_2 are the thresholds, I is an indicator function that has a value one if the argument is true and zero otherwise. The error term is iid with mean zero and finite variance.[7] The threshold is estimated using least squares. The observations are first sorted on the threshold variable and the search for the thresholds is restricted to specific quantiles (the more quantiles the finer the grid to which the search is limited). This reduces the number of regressions and still generates sufficiently precise estimates (see Hansen, 1999, p.

[5] There are three main sources of the data: volumes and prices of value added and labour are taken from the P-series of the National Accounts 1997 of CBS Statistics Netherlands (CBS, 1998). Data on the stock of capital in 1990-prices are provided by the CPB Netherlands Bureau for Economic Policy Analysis. Data on the use of energy and the price of energy are based on the publication *De Nederlandse Energiehuishouding* (CBS, various issues). Some data series had to be constructed; the methodology applied is described in Appendix A. More information is available in Kuper and Van Soest (1999).

[6] It is possible to calculate triple thresholds instead of two as in equation (14).

[7] This iid assumption rules out lagged dependent variables.

349-350). Bootstrapping simulates the asymptotic distribution of the likelihood ratio test. This test is used to test whether the threshold effect is statistically significant under the null of no threshold. If the null is rejected, similar tests are used to test whether there are one, two or even more thresholds.

In line with our theoretical specification, we take as threshold variable the price of energy relative to the nominal wage rate. Next, we define the explanatory variable y_{it} as the rate of growth of the stock of capital, *i.e*. net investment divided by the stock of capital, and x_{it} as a 3-dimensional vector of regressors, again in rates of growth, consisting of the ratio of the user cost of capital over the wage rate (R/W), the ratio of the price of energy over the wage rate (P_E/W), and the growth rate of gross value added (X). This equation captures the substitution effect as well as an accelerator effect. The sector-specific fixed effect which is included picks up the rate of depreciation, so that the explanatory variable is the ratio of gross investment over the stock of capital. This specification is a simple accelerator investment equation including percentage changes of relative prices. We interpret this equation in the following way. Changes in relative prices lead firms to invest in machines with different technologies. This change of technology is represented by changes in input intensities which in turn reflects the change in relative prices. The increase in the growth rate of value added leads firms to invest more in machines with unchanged input intensities, i.e. firms invest more in existing technologies.

We have a balanced panel consisting of 8 sectors of industry and 16 years of observation (1979-1994). We specify 100 quantiles to limit the search and use 300 bootstrap replications to construct asymptotically valid p-values. We define the ratio of energy prices to the wage rate as threshold variable. In principle the coefficients for all elements of vector x_{it} may be regime-dependent, i.e. dependent on the threshold variable. Experiments suggest that there are level-thresholds if we lag the threshold variable one period. We find strong evidence for thresholds only if the accelerator effect is considered to be regime dependent. The null of no thresholds is rejected at 5%. Next, we find strong evidence for two thresholds: the test statistic F equals 14.1 (the 10%, 5% and 1% critical values are 6.7, 9.6 and 13.0 respectively) and the bootstrap p-value equals 0.007. This means we can reject the null of one threshold at a 1%-significant level. Furthermore, the triple threshold model is rejected (p-value equals 0.12), so we conclude that there are two thresholds. The point estimate of the thresholds γ_1 and γ_2 are 1.41 and 2.60 (where it hits the zero axis in Figures 3 and 4 respectively) and the 95% confidence intervals are [1.32, 2.29] and [2.49, 2.76], these are the values of thresholds γ_1 and γ_2 for which the likelihood ratio lies beneath the dotted lines in Figures 3 and 4.

Figure 3 *Confidence interval construction in a double threshold model.*

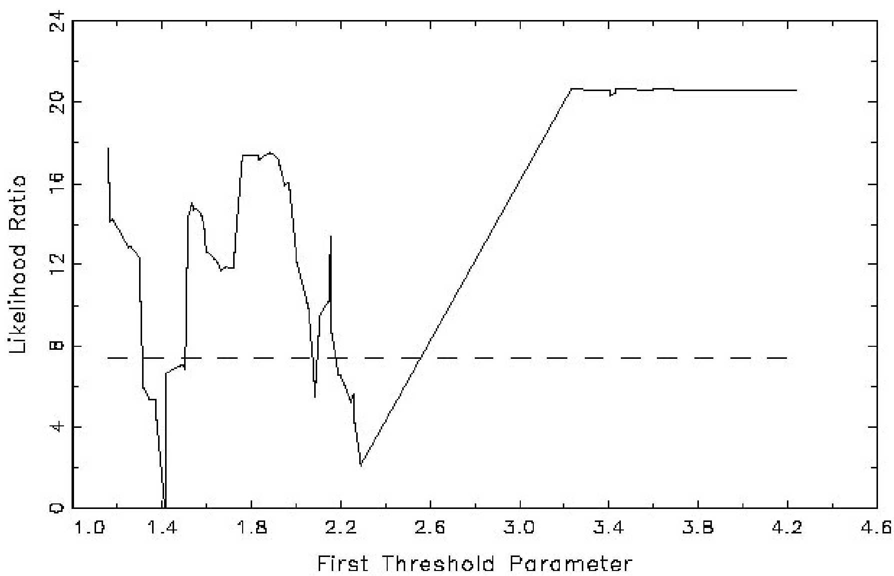


Figure 4 *Confidence interval construction in a double threshold model.*

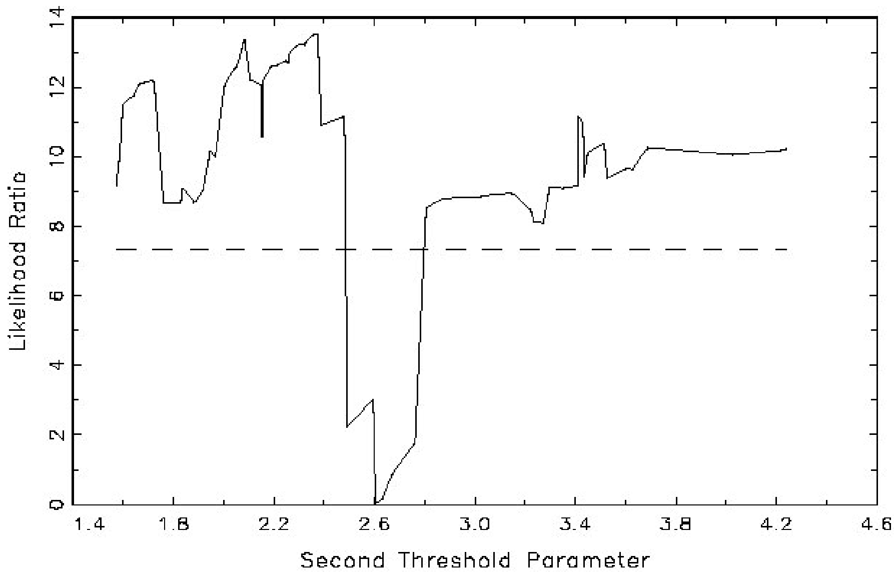


Table 1 summarizes the estimation results. As mentioned above we did not find evidence for regime-dependent effects of changes in relative prices. This implies that the coefficients of the relative price changes are the same across the sample. However, the accelerator differs across regimes. We have identified two thresholds which implies that there are three regimes: $P_E/W \leq 1.41$, $1.41 < P_E/W \leq 2.60$, $P_E/W > 2.60$.

Table 1 *Regression estimates: double threshold model*

Regressor		*Coefficient*	*OLS SE*	*White SE*
Δlog(R/W)		0.023	0.017	0.018
Δlog(P_E/W)		0.026	0.019	0.012
Δlog(X)	I($P_E/W \leq 1.41$)	0.017	0.085	0.044
	I($1.41 < P_E/W \leq 2.60$)	0.489	0.092	0.102
	I($P_E/W > 2.60$)	0.028	0.122	0.082

Relative prices, which are regime-independent, are not very significant. If the price of energy relative to the wage rate is above 1.41 and below 2.60, the accelerator is highly significant. Hence, relative prices seem to matter but in the middle regime (between the thresholds) gross value added is more important. This may be interpreted as relative more investment in existing technologies and less investment in new energy-efficient technologies in the second regime.

It is interesting to know which years and which sectors fall in each of the regimes. Tables 2 and 3 lists the number of observations in each regime per year and per sector. From these tables we draw the following conclusions. The first regime coincides with post-1986 observations, while the third regime is the pre-1986 period. The middle regime is dominated by observations from the post-1986 period. The first regime consists mainly of observations (16 out of 22) from the high energy intensive chemical industry and the basic metal industry.

How do we interpret these results? Relative prices seem to matter most in the chemical industry and the basic metal industry if prices of energy drop relative to wages, i.e. the accelerator effect in these sectors is small and insignificant. This may induce a (faster) return to more energy-using technologies. Other sectors are more reluctant to return to earlier energy-using technologies. These sectors are perhaps hurt more by the earlier rise in energy-prices, and are locked in energy-saving technologies in the sense that these sectors may not find it profitable to return to technologies that reflect the current low energy-prices. Taxing energy in the sectors locked in older technologies will not be very effective.

Table 2 *Number of observations in each regime per year*

Year	*Regime*			
	$I(P_E/W \leq 1.41)$	$I(1.41 < P_E/W \leq 2.60)$	$I(P_E/W > 2.60)$	Total
1979		7	1	8
1980		3	5	8
1981		2	6	8
1982		2	6	8
1983		2	6	8
1984		2	6	8
1985		2	6	8
1986		7	1	8
1987	2	6		8
1988	2	6		8
1989	2	6		8
1990	2	6		8
1991	2	6		8
1992	4	4		8
1993	3	5		8
1994	5	3		8
Total	22	69	37	128

Table 3 *Number of observations in each regime per sector*

	Regime			
	$I(P_E/W \leq 1.41)$	$I(1.41 < P_E/W \leq 2.60)$	$I(P_E/W > 2.60)$	Total
Agriculture		8	8	16
Textiles and clothing		10	6	16
Building materials		10	6	16
Construction	1	10	5	16
Food and beverages	2	8	6	16
Paper industry	3	7	6	16
Chemical industry	8	8		16
Basic metal industry	8	8		16
Total	22	69	37	128

5. Conclusions

This paper aims to shed light on the effectiveness of environmental policy in periods of high and low energy prices. It is argued that while firms are likely to invest in energy-saving technologies when energy prices hit all-time highs, they are unlikely to reverse the investment in periods of lower energy prices. Using Hansen's 1999 threshold estimation technique we do find threshold effect. Only if the price of energy relative to the wage rate is between two thresholds values, firms use existing technologies rather than invest in even less energy-intensive technologies. This implies that in periods of relatively low, and relative high energy prices, small increases in energy taxation perhaps may induce some changes in the production structure. High energy-intensive sectors like the chemical industry and the basic metal industry are more responsive to energy price changes and hence to higher energy taxes.

Appendix A Data construction

Concerning the data used in this paper, three series had to be constructed: the prices and quantities of intermediate output from the first level *Z* and the user cost of capital. The intermediate (composite) output in constant prices can be calculated as the nominal composite output divided by its price index. The value of the composite output in nominal terms equals nominal capital expenditures plus nominal energy expenditures:

(A.1) $P_Z Z \equiv RK + P_E E$.

If we re-scale the prices such that in the base-year P_E=R =1, K and E can be calculated in base-year prices. Then composite output Z is simply Z=K+E. This means that we can calculate the price index of this combined output Z as a weighted average of the price indices of the constituent parts:

(A.2) $$P_Z = \left(\frac{K}{K+E}\right)R + \left(\frac{E}{K+E}\right)P_E \, .$$

Dividing expressions (A.1) and (A.2) yields the volume of input Z.

The (nominal) user cost of capital is not calculated in the usual way.[8] Here, we made use of data on the stock of capital (measured in 1990-prices) kindly provided by CPB, Netherlands Bureau for Economic Policy Analysis. We constructed capital income resulting from production as the gross operating surplus corrected for wage income of self-employed, were self-employed earn the same wage rate as employees. The nominal rental price of capital is now simply calculated as capital income (in current prices) divided by the stock of capital in 1990-prices.

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[8] The most simple Jorgenson type of user cost of capital is $R = P_I(i - \Delta \log P_I + \delta)$, where P_I is the purchase price of a unit of capital, i is the (nominal) interest rate, and δ is the (constant) rate of depreciation.

Finally, given data on the volume of labour input (L), capital input (K) and energy input (E), and their respective prices (W, R and P_E), we can construct gross output in nominal terms as value added in nominal terms plus the value of the energy input: $PQ = WL + RK + P_E E$, where $WL+RK$ equals nominal value added.

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